

**AN ACTIVE FORCE CONTROL (AFC) BASED
CONTROL MOMEN GYROS FOR ATTITUDE
CONTROL OF SMALL SATELLITE**

MOHD BADRUL BIN SALLEH

UNIVERSITI SAINS MALAYSIA

2016

**AN ACTIVE FORCE CONTROL (AFC) BASED CONTROL MOMENT
GYROS FOR ATTITUDE CONTROL OF SMALL SATELLITE**

by

MOHD BADRUL BIN SALLEH

**Thesis submitted in fulfilment of the
requirements for the degree of
Master of Science**

September 2016

ACKNOWLEDGEMENT

All praises are due to Allah. May Allah's peace and blessings be upon His final prophet and messenger, Muhammad, his family and his companions.

First of all, I would like to thank my supervisor, Dr. Nurulasikin Mohd Suhadis for the valuable and continual guidance and encouragement during completing my master study and for her dedication towards my research. The advice and opinion that she'd shared cannot be described in words. I also would like to acknowledge Dr. Muhammad Fadly Adnan Nikmat for being my research reviewer and commentator.

I greatly appreciated the financial support through my supervisor research grant as well as Fellowship Scheme offered by the Institute of Postgraduate Studies (IPS). The supports really helped me to pass through many challenges and at the same time allowed me to experience the real research environment.

Also, thanks to Mr. Mohd Amir Wahab, Mrs. Rahayu Dorahim@Abdul Rahim, Mrs. Zuliana Ismail, my fellow postgraduate and undergraduate students and friends for their helps and supports while completing my work. A special thanks go to Mrs. Anita Arham for proofreading my thesis.

Finally, I would like to express my deepest gratitude to my late mother and my beloved family for never give up supporting and encouraging me in my study life.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF ABBREVIATIONS	xiv
LIST OF SYMBOLS	xvi
ABSTRAK	xxiii
ABSTRACT	xxiv
CHAPTER ONE: INTRODUCTION	
1.1 General Overview	1
1.2 Problem Statements	5
1.3 Research Objectives	6
1.4 Research Scope	6
1.5 Research Approach	6
1.6 Thesis Outline	7
CHAPTER TWO: LITERATURE REVIEW	
2.1 Fundamental Background of CMG	8
2.2 CMG Unit Type	11

2.2.1	SGCMG	11
2.2.2	DGCMG	12
2.2.3	VSCMG	13
2.3	SGCMG-Based Controlled Satellite	16
2.3.1	CMG System Configuration	16
2.3.2	Singularity Problem	19
2.3.3	Three-Axis Attitude Control Technique	26
2.3.4	AFC Technique	30
2.3.5	Gimbal Angle Management	33
2.4	Summary	36

CHAPTER THREE: METHODOLOGY

3.1	Satellite Mission and Configuration	37
3.2	External Disturbances	38
3.2.1	Aerodynamic Torque	38
3.2.2	Solar Radiation Torque	39
3.2.3	Gravity Gradient Torque	40
3.2.4	Magnetic Field Disturbance Torque	41
3.3	Satellite Equations of Motion	41
3.3.1	Coordinate Reference System	41
3.3.2	Attitude Representation	43
3.3.3	Dynamic Equation of Motion	47
3.3.4	Satellite Kinematic	50
3.4	CMG System	50
3.4.1	CMG Dynamics	51

3.4.2	4-SGCMGs System	52
3.4.3	CMG Sizing	54
3.5	Control Strategy	56
3.5.1	Singularity Avoidance Law	57
3.5.2	CMG Torque Control Scheme	57
3.5.3	Quaternion Feedback Controller	58
3.6	AFC Scheme	60
3.7	MTGAC System	62
3.7.1	Geomagnetic Field	63
3.7.2	Magnetic Torque Controller Design	66
 CHAPTER FOUR: RESULTS AND DISCUSSION		
4.1	Simulation Parameters	68
4.2	Singularity Avoidance Analysis	73
4.2.1	Attitude Manoeuvre without Singularity Avoidance Law	73
4.2.2	Attitude Manoeuvre with SR Inverse Steering Law	76
4.3	Attitude Manoeuvre Performances	80
4.3.1	Attitude Manoeuvre with PD Controller	80
4.3.2	Attitude Manoeuvre with PD+AFC	84
4.3.3	Attitude Manoeuvre with PD+AFC+MTGAC	88
4.3.4	Comparison of Attitude Manoeuvre Performance	95
4.4	Attitude Pointing Performances	97
4.4.1	Attitude Pointing with PD Controller	98
4.4.2	Attitude Pointing with PD+AFC	100

4.4.3	Attitude Pointing with PD+AFC+MTGAC	103
4.4.4	Comparison of Attitude Pointing Performance	105

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1	Conclusion	109
5.2	Contribution	111
5.3	Recommendation for Future Works	112

REFERENCES	113
-------------------	------------

LIST OF PUBLICATIONS

LIST OF TABLES

		Page
Table 1.1	Satellite Attitude Control Methods (Larson and Wertz, 1999)	2
Table 2.1	Comparison of Different CMG Types (Lappas, 2002; Sangwon, 2010)	11
Table 4.1	Orbit Parameters	68
Table 4.2	Satellite with 4-SGCMGs System Specification	69
Table 4.3	External Disturbance Torques	70
Table 4.4	PD Controller Parameters	72
Table 4.5	AFC Parameters Tunings	84
Table 4.6	MTGAC System Parameters	91
Table 4.7	Attitude Pointing Errors with Different Controllers	108
Table 4.8	Attitude Pointing Enhancement with respect to PD Controller	108

LIST OF FIGURES

		Page
Figure 1.1	Satellite System Design Architecture (Larson and Wertz, 1999)	1
Figure 2.1	Basic Structure of a Gyroscope (Nave, 2016)	8
Figure 2.2	Illustrations of Gyroscope Properties (Nave, 2016)	9
Figure 2.3	Diagram of Rate Gyroscope; O_ζ , O_η and O_ξ are the Axes of the Reference System; O_x , O_y and O_z are the Axes of the Gimbal Ring (Ishlinskii and Rivkin, 2010)	10
Figure 2.4	A unit of SGCMG (Kurokawa, 1998)	12
Figure 2.5	A unit of DGCMG (Kurokawa, 1998)	13
Figure 2.6	A unit of VSCMG; $\hat{\mathbf{g}}_s$ is the spin axis unit vector, $\hat{\mathbf{g}}_g$ is the gimbal axis unit vector, $\hat{\mathbf{g}}_t$ is the torque axis unit vector, $\dot{\gamma}$ is the gimbal angle rate and $\boldsymbol{\Omega}$ is the non-constant rotational speed of the VSCMG's flywheel (Richie et al., 2001)	13
Figure 2.7	Basic Block Diagram of a CMG-Based Attitude Control System for Agile Imaging Satellites (Wie, 1998)	16
Figure 2.8	Different Type of SGCMGs System Configurations (Kurokawa, 1998)	18
Figure 2.9	Three DGCMGs cluster used on the Skylab (Chubb and Seltzer, 1971)	18
Figure 2.10	Types of Singularity (Emre, 2003)	20

Figure 2.11	Momentum Envelope of 4-SGCMGs System in Pyramid Configuration where Dimples Indicate the Gimbal Axes of 4-SGCMGs (Paradiso, 1992)	21
Figure 2.12	Internal Singular Surface of 4-SGCMGs System in Pyramid Configuration (Takada et al., 2010)	21
Figure 3.1	Satellite Configuration with 4-SGCMGs and Three Magnetic Torquers	38
Figure 3.2	Coordinate Reference Frames	42
Figure 3.3	The Euler Angles: Roll ϕ , Pitch θ and Yaw ψ	43
Figure 3.4	Euler's Rotational Theorem of a Quaternion	44
Figure 3.5	Control Moment Gyroscope Diagram	51
Figure 3.6	4-SGCMGs Cluster in Pyramid Configuration	53
Figure 3.7	Angular rate and CMG torque diagram showing the maximum satellite's angular rate $\dot{\theta}_s^{max}$, required CMG control torque \dot{h}_{CMG}^{req} and satellite's angular acceleration $\ddot{\theta}_s$	55
Figure 3.8	CMG-Based Attitude Control Scheme	60
Figure 3.9	Active Force Control (AFC) Schematic Block Diagram	61
Figure 3.10	Arrangement Three Magnetic Torquers	62
Figure 3.11	Illustration of the Earth's Magnetic Field Lines	63

Figure 3.12	MTGAC System Integrated into the Closed-Loop Attitude Control System of the AFC Based CMG-Controlled Small Satellite	67
Figure 4.1	External Disturbance Torques	71
Figure 4.2	Attitude Manoeuvre Performance without Singularity Avoidance Law for $\delta_{init} = [0 \ 0 \ 0 \ 0]^T$ degree	74
Figure 4.3	Attitude Manoeuvre Performance without Singularity Avoidance Law for $\delta_{init} = [70 \ 0 \ -70 \ 0]^T$ degree	75
Figure 4.4	Attitude Manoeuvre Performance without Singularity Avoidance Law for $\delta_{init} = [-90 \ 0 \ 90 \ 0]^T$ degree	76
Figure 4.5	Attitude Manoeuvre Performance with SR Inverse Steering Law for $\delta_{init} = [0 \ 0 \ 0 \ 0]^T$ degree	77
Figure 4.6	Attitude Manoeuvre Performance with SR Inverse Steering Law for $\delta_{init} = [70 \ 0 \ -70 \ 0]^T$ degree	78
Figure 4.7	Attitude Manoeuvre Performance with SR Inverse Steering Law at $\delta_{init} = [-90 \ 0 \ 90 \ 0]^T$ degree	79
Figure 4.8	Attitude Angles of the Satellite with PD Controller	81
Figure 4.9	Angular Rates of the Satellite with PD Controller	81
Figure 4.10	Control Torques Generated with PD Controller	82
Figure 4.11	Angular Momentums of the Satellite with PD Controller	82
Figure 4.12	Gimbal Angles of the CMG System with PD Controller	83

Figure 4.13	Gimbal Angle Rates of the CMG System with PD Controller	83
Figure 4.14	Attitude Angles of the Satellite with PD+AFC	85
Figure 4.15	Angular Rates of the Satellite with PD+AFC	86
Figure 4.16	Control Torques Generated with PD+AFC	86
Figure 4.17	Angular Momentums of the Satellite with PD+AFC	87
Figure 4.18	Gimbal Angles of the CMG System with PD+AFC	87
Figure 4.19	Gimbal Angle Rates of the CMG System with PD+AFC	88
Figure 4.20	Gimbal Angle of the CMG System without MTGAC System	89
Figure 4.21	Angular Momentum of the Satellite without MTGAC System	90
Figure 4.22	Attitude Angles of the Satellite without MTGAC System	90
Figure 4.23	Gimbal Angle Errors at Different t_c	91
Figure 4.24	Attitude Angles of the Satellite with PD+AFC+MTGAC	92
Figure 4.25	Angular Rates of the Satellite with PD+AFC+MTGAC	93
Figure 4.26	Control Torques Generated with PD+AFC+MTGAC	93

Figure 4.27	Angular Momentums of the Satellite with PD+AFC+MTGAC	94
Figure 4.28	Gimbal Angles of the CMG System with PD+AFC+MTGAC	94
Figure 4.29	Gimbal Angle Rates of the CMG System with PD+AFC+MTGAC	95
Figure 4.30	Comparison of Roll during Attitude Manoeuvre Operation	96
Figure 4.31	Comparison of Pitch during Attitude Manoeuvre Operation	96
Figure 4.32	Comparison of Yaw during Attitude Manoeuvre Operation	97
Figure 4.33	Attitude Accuracies of the Satellite with PD Controller	98
Figure 4.34	Gimbal Angles of the CMG System with PD Controller	99
Figure 4.35	Angular Momentums of the Satellite with PD Controller	99
Figure 4.36	Singularity Index of the CMG System with PD Controller	100
Figure 4.37	Attitude Accuracies of the Satellite with PD+AFC	101
Figure 4.38	Gimbal Angles of the CMG System with PD+AFC	101
Figure 4.39	Angular Momentums of the Satellite with PD+AFC	102
Figure 4.40	Singularity Index of the CMG System with PD+AFC	102

Figure 4.41	Attitude Accuracies of the Satellite with PD+AFC+MTGAC	103
Figure 4.42	Gimbal Angles of the CMG System with PD+AFC+MTGAC	104
Figure 4.43	Angular Momentums of the Satellite with PD+AFC+MTGAC	104
Figure 4.44	Singularity Index of the CMG system with PD+AFC+MTGAC	105
Figure 4.45	Comparison of Roll during Attitude Pointing Operation	106
Figure 4.46	Comparison of Pitch during Attitude Pointing Operation	106
Figure 4.47	Comparison of Yaw during Attitude Pointing Operation	107

LIST OF ABBREVIATIONS

ADCS	Attitude Determination and Control System
AFC	Active Force Control
AFCCA	Active Force Control Crude Approximation
AFCCAIL	Active Force Control Crude and Iterative Learning
ASCMG	Adaptive-Skew Control Moment Gyroscope
CEACS	Combined Energy and Attitude Control System
CMG	Control Moment Gyroscope
CMG-RW	Control Moment Gyroscope-Reaction Wheel
COTS	Commercially of The Self
DGCMG	Double Gimbal Control Moment Gyroscope
IGRF	International Geomagnetic Reference Field
IPACS	Integrated Power and Attitude Control System
ISS	International Space Station
LEO	Low Earth Orbit
LQ	Linear Quadratic
LVLH	Local Vertical Local Horizontal
MED	Momentum Exchange Device
MP	Moore-Penrose
MTGAC	Magnetic Torque Gimbal Angle Compensation
PD	Proportional-Derivative
PD+AFC	Proportional-Derivative+Active Force Control
PD+AFC+MTGAC	Proportional-Derivative+Active Force Control+ Magnetic Torque Gimbal Angle Compensation

PI	Proportional-Integral
PID	Proportional-Integral-Derivative
rpm	Rotation per minute
RW	Reaction Wheel
SGCMG	Single Gimbal Control Moment Gyroscope
SR	Singularity Robust
SSTL	Surrey Satellite Technology Ltd
SVD	Single Value Decomposition
TPM	Torque Product Minimization
VPDRF	Variable Periodic Disturbance Rejection Filter
VSCMG	Variable Speed Control Moment Gyroscope

LIST OF SYMBOLS

α	Orbit angle measure from the ascending node
β	Pyramid skew angle/Angular momentum precession angle
$\dot{\gamma}$	Gimbal angle rate of VSCMG
Δ	Differences between two values
δ	Gimbal angles vector of SGCMGs
δ_{init}	Initial gimbal angles vector
δ_{final}	Final gimbal angles vector
δ^*	Preferred gimbal angles vector
δ_e	Maximum gimbal angle error
$\delta_{e_{avg}}$	Average value of maximum gimbal angle error
$\dot{\delta}$	Gimbal angle rates vector
$\dot{\delta}_e$	Gimbal angle error rates vector
$\dot{\delta}$	Gimbal angle rate
$\dot{\delta}_i$	Gimbal angle rate of i^{th} VSCMG
$\dot{\delta}_{max}$	Gimbal angle rates limit
ζ	Damping ratio
η_m	Phase angle
ϑ	True anomaly
θ	Pitch angle
θ_s	Attitude angle of the satellite
$\dot{\theta}_s$	Angular rate of the satellite
$\dot{\theta}_s^{max}$	Maximum angular rate of the satellite

$\ddot{\boldsymbol{\theta}}'$	Measured acceleration of the dynamic system
$\ddot{\boldsymbol{\theta}}_s$	Satellite angular acceleration vector
$\ddot{\theta}_s$	Angular acceleration of the satellite
λ	Singularity robust (SR) inverse steering law constant
μ_{\oplus}	Earth gravitational constant ($398600 \text{ km}^3/\text{s}^2$)
ξ_m	Instantaneous inclination
ρ	Atmospheric density
ϕ	Roll angle
ψ	Yaw angle
$\boldsymbol{\omega}$	Satellite angular velocity vector
$\boldsymbol{\omega}_{\mathbf{I}/\mathbf{B}}$	Inertially referenced satellite's angular velocity relative to inertial coordinate system
ω	Argument of perigee
ω_E	Earth's orbital frequency
ω_n	Natural frequency
ω_0	Orbital frequency
$\dot{\boldsymbol{\omega}}$	Satellite angular acceleration vector
$\dot{\boldsymbol{\omega}}_{\mathbf{I}/\mathbf{B}}$	Inertially referenced satellite's angular acceleration relative to inertial coordinate system
ω_{CMG}	Angular velocity of the CMG's flywheel
$\boldsymbol{\Omega}$	Non-constant rotational speed of VSCMG's flywheel
$\boldsymbol{\Omega}(\boldsymbol{\omega})$	4×4 Skew symmetric matrix
Φ	Euler rotation angle
Υ	Vernal equinox

$\mathbf{A}(\boldsymbol{\delta})$	Jacobian matrix
\mathbf{A}^+	Pseudoinverse of Jacobian matrix
\mathbf{A}^T	Transposed of Jacobian matrix
$\mathbf{A}^\#$	Singularity robust inverse
\mathbf{A}_s	Satellite's exposed area
$[\mathbf{A}(\mathbf{q})]$	Direction cosine matrix expressed in quaternion
a	Orbit semimajor axis
\mathbf{B}	Geomagnetic field vector
B	Magnitude of the geomagnetic field vector
\mathbf{C}_D	Drag coefficient
\mathbf{C}_g	Centre of gravity
C_s	Solar radiation constant (1358 W/m ²)
\mathbf{C}_{sp}	Centre of solar pressure
c	Speed of light (3.0×10^8 m/s)
D	Residual magnetic dipole moment
\mathbf{e}	Eigenvector of rotation, $\mathbf{e} = [e_1 \ e_2 \ e_3]^T$
F	Solar force
$\hat{\mathbf{g}}_s, \hat{\mathbf{g}}_g, \hat{\mathbf{g}}_t$	Spin, gimbal and torque axes unit vectors
\mathbf{H}	Total angular momentum of the system
$\dot{\mathbf{H}}_B$	Rate of change of satellite's angular momentum in satellite's body frame
$\dot{\mathbf{H}}_I$	Rate of change of satellite's angular momentum in inertial coordinate system
\mathbf{h}	CMG system angular momentum vector
h	Orbital altitude/angular momentum of flywheel

h_i	Angular momentum of i^{th} VSCMG
h_0	Angular momentum magnitude of SGCMG
h_x, h_y, h_z	Angular momentum along satellite's body axes
h'	Rotated angular momentum of flywheel
\mathbf{h}	Generated CMG torque vector
$\dot{h}_x, \dot{h}_y, \dot{h}_z$	Generated CMG torque along satellite's body axes
\dot{h}_{CMG}	Generated CMG torque
\dot{h}_{CMG}^{req}	Required CMG torque
\mathbf{I}	Satellite's moment of inertia tensor/Principle moment of inertia
I_x, I_y, I_z	Principle moment of inertia along satellite's body frame
\mathbf{I}'	Estimated inertia vector of the dynamic system
I_{CMG}	Moment of inertia of the CMG
i	Orbit inclination
i_s	Incidence angle
J_i	Moment of inertia of i^{th} VSCMG
\mathbf{K}_d	Derivative attitude control gain
\mathbf{K}_p	Proportional attitude control gain
\mathbf{M}	Magnetic dipole moment generated by the magnetic torquers
$\mathbf{M}_{\text{limit}}$	Moment acting on the satellite's body/Magnetic dipole moment saturation of the magnetic torquers
M	AFC gain
M_e	Earth's magnetic dipole, (7.9×10^{15} Wbm)

m	Singularity index
m_s	Satellite total mass
m_{CMG}	CMG system total mass
O_ζ, O_η, O_ξ	Axes of the gimbal ring
O_x, O_y, O_z	Axes of the reference frame
\mathbf{q}	Quaternion vector
\mathbf{q}_c	Commanded quaternion vector
\mathbf{q}_e	Quaternion error vector
\mathbf{q}_o	Output quaternion vector
$q_{i=1,2,3}$	Vector elements of the quaternion
q_4	Scalar which gives the magnitude of the rotation angle
q_r	Reflectivity factor
\mathbf{q}^*	Complex conjugate quaternion
\mathbf{q}_{norm}	Normalized quaternion
$\ \mathbf{q}\ $	Quaternion norm
R	Distance from the centre of the Earth
R_e	Radius of the Earth $R_e = 6370$ km
R_o	Orbital radius of the satellite
\mathbf{RPY}_{init}	Initial satellite attitude (R – roll along X_B axis, P – pitch along Y_B axis and Y – yaw along Z_B axis)
\mathbf{RPY}_{ref}	Reference/desired satellite attitude (R – roll along X_B axis, P – pitch along Y_B axis and Y – yaw along Z_B axis)
$\mathbf{S}(\omega)$	3×3 Skew symmetric matrix
\mathbf{s}_i	Spin axis vector

T	Orbital period
\mathbf{T}_{aero}	Aerodynamic torque vector
T_{aero}	Aerodynamic torque
$T_{\text{aero,constant}}$	Constant component of aerodynamic torque
$T_{\text{aero,harmonic}}$	Harmonic component of aerodynamic torque
$T_{\text{aero,max}}$	Maximum aerodynamic torque
\mathbf{T}_{c}	Required magnetic torque vector
\mathbf{T}_{d}	External disturbance torque vector
T_{dx}, T_{dy}, T_{dz}	External disturbance torques exerted on the satellite body
\mathbf{T}_{gg}	Gravity-gradient torque vector
\mathbf{T}_{ext}	External torque vector
$\mathbf{T}_{\text{magnetic}}$	Magnetic disturbance torque vector
\mathbf{T}_{M}	Magnetic torque vector
\mathbf{T}_{O}	Output torque of VCMG
\mathbf{T}_{sp}	Solar radiation torque vector
$T_{\text{solar,constant}}$	Constant component of solar radiation torque
$T_{\text{solar,harmonic}}$	Harmonic component of solar radiation torque
$T_{\text{solar,max}}$	Maximum solar radiation torque
\mathbf{T}'_{cmg}	Measured actuator torque vector
\mathbf{T}'_{d}	Estimated disturbance torque vector
t	Time
t_c	Gimbal angle converging time
\mathbf{t}_i	Torque axis vector

\mathbf{u}	Internal control torque generated by the CMG system
V	Satellite's velocity
$W(s)$	Weighting function
(X_I, Y_I, Z_I)	Inertia frame coordinate system
(X_O, Y_O, Z_O)	Orbit reference frame coordinate system
(X_B, Y_B, Z_B)	Satellite's body frame coordinate system
\otimes	Quaternion multiplication operator

GIROSKOP KAWALAN MOMEN BERASASKAN KAWALAN DAYA AKTIF (AFC) UNTUK KAWALAN ATITUD SATELIT KECIL

ABSTRAK

Sistem giroskop kawalan momen (CMG) adalah pilihan yang sesuai untuk bagi rekabentuk sistem kawalan atitud (ACS) satelit kecil bagi misi berprestasi tinggi kerana ia memiliki amplifikasi kilasan yang tinggi. Namun, kebolehan sistem ini adalah terhad dengan kehadiran unsur gangguan kerana limitasi pengawal atitud piawai untuk menolak gangguan tersebut secara teguh selain sistem CMG yang berdepan dengan masalah sudut gimbal tersesar. Dalam kajian ini, kawalan daya aktif (AFC) dicadangkan dan diintegrasikan bersama pengawal berkadaran-terbitan bagi mengarah sistem CMG menjana kilasan kawalan bagi misi yang ditetapkan manakala sistem pampasan sudut gimbal kilasan magnetik (MTGAC) diintegrasikan ke dalam ACS untuk memampas gimbal tersesar sudut. Kesemua model matematik dibina dan dilaksanakan dalam perisian Matlab[®]-Simulink[™]. Berdasarkan simulasi, skema AFC yang dicadangkan sangat mempengaruhi prestasi manuver atitud dan tudingan atitud satelit. Dengan memilih parameter AFC yang sesuai, manuver atitud yang dikehendaki dapat dicapai dan ralat atitud dapat dikurangkan dengan ketara lebih dari 60%. Manakala, sistem MTGAC berjaya mengekalkan gimbal-gimbal GKM pada sudut yang dikehendaki lantas meletakkan sistem CMG jauh dari ketunggalan. Tambahan itu, sistem MTGAC juga memberi darjah kebebasan tambahan kepada kawalan tudingan atitud apabila ia menambahbaik ketepatan atitud sebanyak 75% tanpa mempengaruhi prestasi manuver atitud satelit. Penemuan kajian ini telah pertama kalinya mendemonstrasikan keandalan skema AFC and MTGAC bagi satelit kecil dengan sistem CMG yang sebelum ini belum pernah dikaji.